A Study of Internal Waves and Turbulence above Irregular, Sloping Bathymetry: A Contribution to the Littoral Internal Wave Initiative (LIWI)

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Award #: N00014-97-1-0087
http://hrp.whoi.edu/hrpgrp/liwi/twist1.html

LONG-TERM GOALS

The long-range goal of our studies is to understand the processes that cause mixing in the ocean. Of particular interest is the turbulence caused by internal wave breaking. Our recent work has revealed strong relationships between finescale shear levels and the intensity of turbulent mixing, and marked spatial variability in the intensity and characteristics of the internal wave field. In particular, we have found enhanced finestructure and microstructure adjacent to rough bathymetric structures. We seek to develop sufficient understanding of internal waves near such bathymetry as to produce models that can predict the magnitude and variability of turbulent mixing resulting from internal wave breaking.

OBJECTIVES

A field program was conducted in May of 1998 in order to quantify finescale internal wave characteristics above a region of irregular, sloping bathymetry. Analysis of the data will focus upon two basic mechanisms for modifying the internal wave field in the littoral zone: internal wave generation at, and wave reflection from, the bottom. Both can result in enhanced internal wave shear and strain, and in turn, increased occurrence of shear and/or advective instability supporting turbulence and mixing.

Our objectives in this current grant are two fold. First, we will relate the field measurements to the generation/reflection processes which may produce enhanced finescale internal waves. Specifically, we will be testing and refining models of wave generation/reflection. Secondly, we will develop and test dynamical models which predict the spatial and temporal evolution of an enhanced finescale internal wavefield as it propagates away from the bottom boundary. Such dynamical models will result in a prediction of the rate at which internal wave energy dissipates and results in turbulent mixing.

APPROACH

Our approach to the field program was to utilize a combination of vertically profiling instrumentation. The first instrument is the freely falling High Resolution Profiler (Schmitt *et al*., 1988) which obtains samples of the ocean's temperature, salinity, and horizontal velocity field and the associated dissipation rates of turbulent kinetic energy and temperature variance. The second instrument is a moored profiling instrument system (termed the Moored Velocity Profiler, MVP) which is able to sample oceanic finescale velocity, temperature and salinity variability. Third, we brought along, and made significant use of, a Lowered Acoustic Doppler Current Profiler/Conductivity Temperature Depth (LADCP/CTD) system. Finally, Eric Kunze from the University of Washington deployed expendable instrumentation [eXpendable Current Profilers (XCPs) and eXpendable CTDs (XCTDs)] during the cruise.

The experimental site is characterized by well defined, small horizontal scale (2.5-3 km horizontal wavelength) ridges oriented onshore-offshore and superimposed on a large-scale planar slope, Figure 1. Three MVP's were deployed as a coherent array with an approximate spacing of 500 m. The array was located in about 1150 m water depth on the continental slope just north of Cape Hatterras (36 34'N, 74 39'W). The HRP was used to repeatedly sample a grid of stations in water depths of 800-1800 m about the MVP array. The LADCP/CTD was typically deployed in water depths shallower than 800 m. Expendable operations were concentrated on a site 10 km to the north of the moored array. In combination, these vertical profile data will allow us to characterize the amplitude and direction of propagation of the finescale internal wavefield. This information will permit an assessment of the various generation/reflection processes.

Our research effort benefits from the technical support of several people here at WHOI. Ellyn Montgomery maintains the HRP sensors and control processor and its associated data acquisition and reduction systems. The instruments mechanical systems are maintained by David Wellwood. Maggie Cook and Gwyneth Packard assist the PI's with reduction and analysis of the acquired data. The Moored Velocity Profiler technical activities are being supported by folks in the Institution's Advanced Engineering Laboratory.

WORK COMPLETED

Cruise preparations were completed. This included: the construction of two MVPs and refurbishment of a third, development of software for the analysis of MVP data, and analysis of existing ancillary data (i.e. historical current meter and CTD data) to refine the sampling strategy. Cruise preparations were complicated by an explosion within the HRP pressure case, which apparently was triggered by a faulty battery.

The cruise was a success even though the HRP was temporarily lost and we needed to repair and redeploy two of the MVP's. Despite these difficulties, we came back with the high quality data we intended to acquire. Roughly 90% of the intended grid sampling was accomplished with either the

LADCP/CTD or the HRP. In total, 214 HRP, 48 LADCP/CTD and 108 XCP/XCTD profiles were obtained. Approximately 815 velocity and CTD profiles were obtained from the MVPs. We are still at the stage of processing data from the field program.

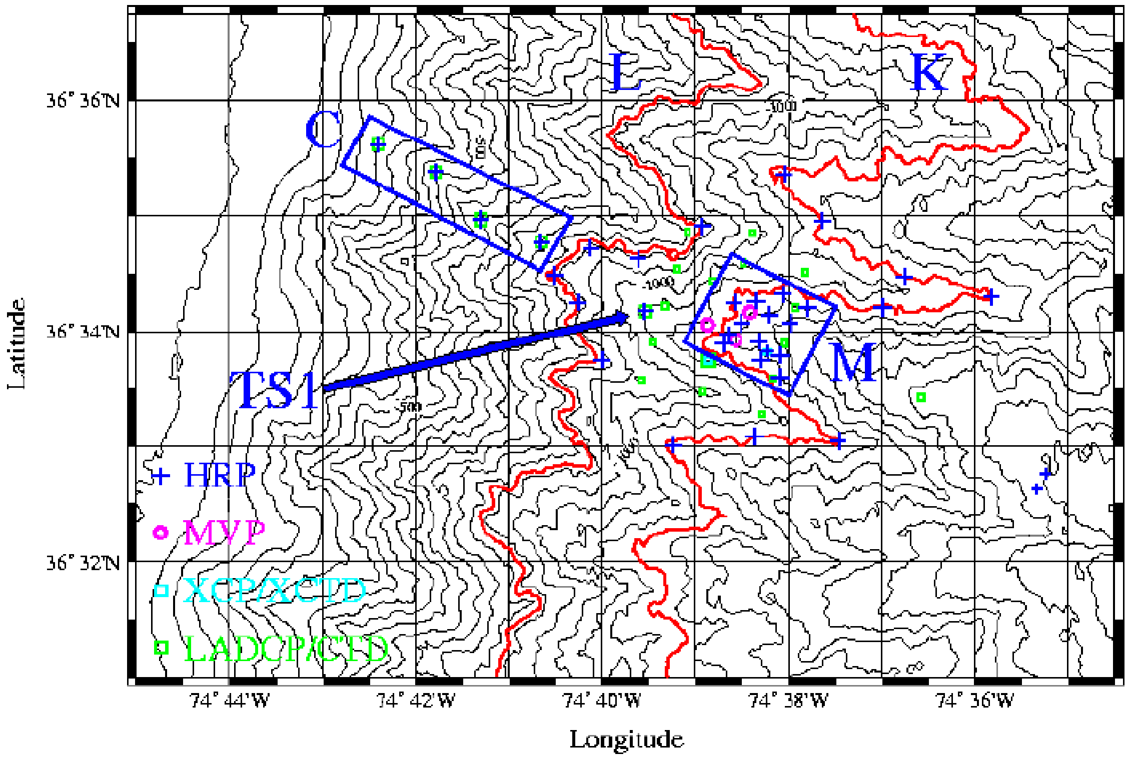

Figure 1: Sampling plan for the field program. Bathymetry is contoured at intervals of 100 m. The symbol and color key for the various instruments appears within the plot. Large symbols denote reoccupied stations. The red bathymetric contours denote water depths of 880 and 1150 m. The HRP work was confined to these bathymetric contours for most of the field program. The 'L' and 'K' notation signifies grids of reoccupied stations on the 880 and 1150 m isobaths, respectively. The 'M' notation denotes a repeated grid about the MVP array, and 'C' denotes an across-shelf grid in water shallower than 800m. A time series is depicted with the notation 'TS1'.

RESULTS

Preliminary analysis of the data reveals that turbulent mixing was greatly enhanced above rough bathymetry on the Continental Slope (not shown). Vertical profiles of turbulent diffusivity $K_\rho = 0.25\varepsilon / N^2$ uniformly indicate a bottom enhancement. At the moored array, the turbulent diffusivity in the bottom 200 m is approximately 20 x 10^{-4} m^2 s^{-1}, more than two orders of magnitude larger than that estimated in the upper 100 m of the water column. Further offshore, where the bottom is relatively smooth, the turbulent diffusivity decreases. Within the Gulf Stream, vertical mixing is weak (O~10^{-5} m^2 s^{-1}) and independent of depth.

The HRP data indicate a maximum in turbulent dissipation (□) during the middle portion of the field program (Figure 2). This temporal variability in the dissipation rate can be linked to distinct, high vertical wavenumber features in both the HRP and MVP velocity profiles. They appear most prominently in the across-slope velocity records. By low- and band-passing the MVP velocity profiles in the time domain, these high wavenumber features are found to have sub-inertial Eulerian periods (Figure 3). Interestingly, their occurrence appears related to a transition in the background, along-slope currents. At periods greater than three days, the along-slope currents are originally northward and increase with height above bottom (Figure 3a). The low-frequency along-slope currents oscillate with time and large dissipations coincide with the largest along-slope currents. During this time of large southward flow, small vertical wavelength features having amplitudes of 5 cm/s appear in the across-slope velocity profiles. These features have Eulerian frequencies which are smaller than f (Figure 3, b and c).

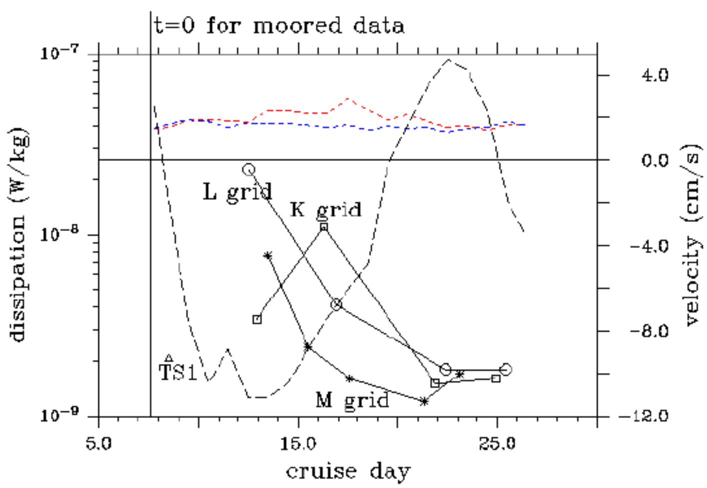

Figure 2: Symbols denote the average dissipation below 500 db for individual occupations of the grids or time series stations in Figure 1. The daily average along-slope (positive northward) current below 500 db at the MVP array is given by the dashed line. A fourth order polynomial was fit to both the eastward and northward currents over 500-1100 db. The rms residual currents are plotted as the blue (northward ~ along-slope) and red (eastward ~ across-slope) dashed lines. These residuals represent the high wavenumber fluctuations apparent in Figure 3.

Our hypothesis is that these high wavenumber features in the across-slope velocity profiles represent a transient internal lee wave response to the lower frequency, along-slope flow over the rough bathymetry. Further work will seek to determine if this is true.

IMPACTS/APPLICATIONS

As part of this grant, a novel dynamical model was developed which permits the assessment of wave propagation and non-linear interactions in determining the energy balance of the finescale internal wavefield. While the model is highly idealized in it's present form, we expect that appropriate modifications can be made to provide robust estimates of the spatial and temporal evolution of the internal wavefield and turbulent dissipation in continental slope regions. The field program described above will help ground truth the model.

TRANSITIONS

A manuscript describing the dynamical model results outlined above is in preparation. The results have been presented in seminars at the University of Washington, University of Victoria, Woods Hole Oceanographic Institution, and Bedford Institute of Oceanography. We have invited Steve Thorpe (Univ. of Southampton) to the United States to explore collaborative projects. Dr. Thorpe obtained ONR funding to do so. Sonya Legg (WHOI) has obtained ONR funding for numerical studies of internal wave processes in the littoral zone. We anticipate working closely with Dr. Legg.

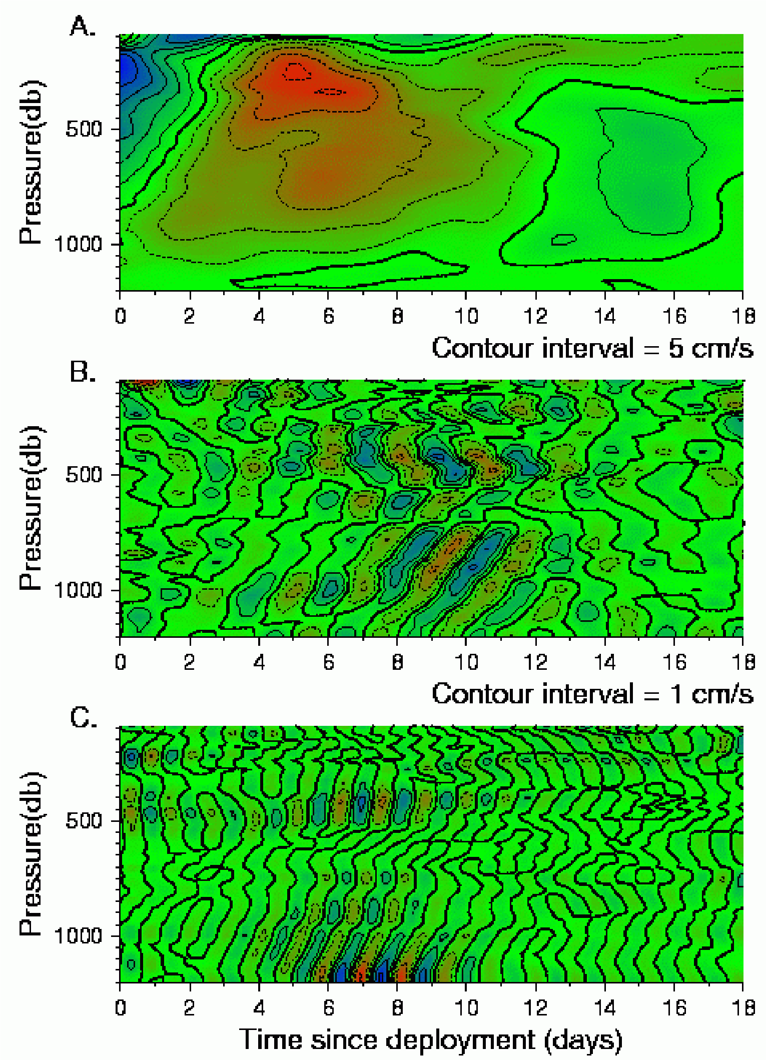

Figure 3: Contours of frequency filtered velocity plotted against time and pressure. Panel A: Along-slope velocity features with periods longer than 72 hrs, contoured at a 5cm/s interval. Panel B: Across- slope velocity with periods between 45 and 72 hrs, contoured at a 1cm/s interval. Panel C: Across-slope velocity with periods between 26 and 32 hrs, contoured at a 1cm/s interval. All panels feature a bold zero contour associated with a green background. Negative velocities are displayed in red with a dashed contour; positive values are displayed in blue with a solid contour.

RELATED PROJECTS

We used three Moored Velocity Profilers in the field experiment. Alterations to the pre-exisiting Moored Profiler, which carried only a CTD, were funded by ONR (grant to J. Toole and R. Schmitt). As well, refurbishing of the prototype MVP and construction of two new MVP's was funded under a companion DURIP grant (J. Toole and D. Frye). Eric Kunze (UW, XCP and XCTD deployment) participated in the field program. Finally, the insight gained as part of this grant will have a direct impact on the interpretation of HRP and tracer data acquired during the Brazil Basin Experiment (NSF grants to J. Ledwell, J. Toole and R. Schmitt).

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PATENTS

U.S. patent awarded August 1998 for the WHOI Moored Profiler, Co-Inventors K. Doherty, D. Frye and J. Toole